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UNPUBLISHED PRELIMINARY DATA

Observational Work on Cosmic Gamma Rays*

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In recent years a variety of efforts have been made at MIT to observe cosmic photons in the range of energies from 10^4 ev to over 10^{15} ev. I would like to review four of these efforts starting from the bottom and working up in energy.

Naive power-low extrapolations of the measured flux densities of x-rays near 4 Kev from the recently discovered cosmic x-ray sources predict intensities above 15 Kev which should be detectable at the highest attainable balloon altitudes. In contrast, the blackbody spectra expected from the surfaces of neutron stars, which came into vogue one year ago as possible sources of the newly discovered cosmic x-rays, should cut off sharply below 10 Kev. It, therefore, appears that balloon measurements of x-ray spectra in the 15 Kev to 60 Kev can provide a test of the neutron star hypothesis. Furthermore, the general prospects of balloon x-ray observations are

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attractive for a variety of practical reasons. These considerations led to a recent successful attempt to observe cosmic x-rays in a balloon experiment.[1]

For this observation, I prepared a scintillation detector consisting of a thin crystal of NaI(Tl) optically coupled to a 5" high gain photomultiplier. The pulses were analyzed and recorded in five pulse height channels from 9 Kev to over 62 Kev. In front of the detector was a frame of brass slats which defined a field of view that was 32° wide by 110° long. The package was oriented with the axis of the detector inclined at 35° from the zenith, and the 110° direction was in a vertical plane. During the flight the package was rotated about a vertical axis by a rotator and the instantaneous azimuth of the detector axis was determined by interpolating between periodic readings of a magnetometer.

The balloon was launched at dawn on July 20, 1964 and reached its maximum altitude of 133,000 feet three hours before the meridian transit of the Crab Nebula. During the next 80 minutes, while the balloon remained above a pressure altitude of 3.9 mb and the package rotated about a vertical axis, the diurnal motion of the Crab Nebula carried it from 35° to 18° in zenith angle and from 96° to 118° in azimuth.

Figure 1 shows the observed counting rates in the five pulse height channels plotted as a function of the azimuth of the detector axis measured relative to the Crab Nebula. A peak in the counting rates in the three middle channels is clearly evident near zero relative azimuth when the Crab Nebula was within the field of view. Since the Crab Nebula is the only known source of lower energy x-rays in this field of view it is likely to be also the source of the higher energy radiation observed here. The small discrepancy between the apparent position of the peaks and zero relative azimuth can be accounted for as systematic error in the magnetic field measurement.

I calculated the relative counting rates in the five pulse height channels expected for various hypothetical incident x-ray spectra, taking into account atmospheric absorption along the slant direction to the Crab Nebula, and the efficiency and energy resolution of the scintillation detector. Figure 2 shows the results for three trial spectra. The values are all normalized to the observed rate in channel III. The temperature of 80 million degrees required to fit a blackbody spectrum to the data is far higher than the surface temperatures predicted for neutron stars. This observation is therefore strong new evidence against the simple neutron star hypothesis for the x-ray source in the Crab Nebula.

The data from direct observations now available on the electromagnetic spectrum of the Crab Nebula are summarized in Figure 3. The radio region is well established. The accuracy of the optical and UV results suffers from substantial uncertainties in the corrections for attenuation by interstellar dust. The data near 10^{18} c/s was calculated from the most recent results of the NRL rocket experiments. The results of the present experiment are indicated by a short piece of a power law with spectral index 2 fitted to the data.

The second experiment that I would like to describe is one carried out in February 1964 by J. Overbeck to test whether the SCO-X1 source is a cloud of energetic electrons producing x-rays by inverse Compton scattering of starlight.(2) M. Oda and I had pointed out previously that such a cloud, lying at a distance of about 50 l.y., would have to have a total energy in relativistic electrons about equal to that released by a supernova in order to give the observed X-ray intensity.[3] Subsequently, P. Morrison suggested than an ancient explosion in the galactic nucleus may have generated the required electron cloud which is presently moving out along the galactic axis where we observe it as SCO-X1.[4] In any case, if such a cloud is the source of the observed X-rays, it must also be a source of bremsstrahlung gamma rays produced in collision between the electrons and the ambient gas. Overbeck searched for these gamma rays in a balloon experiment at 115,000 feet in which he periodically interposed a lead shield between a large gamma ray detector and SCO-X1. The apparatus is shown schematically in Figure 4. He obtained negative results which appear to eliminate the inverse Compton effect as a mechanism for the x-ray production.

To see how the implications of Overbeck's experiment work out quantitatively we note first that the average energy of the recoil photons produced in Compton collisions between electrons of energy E and isotropic photons of energy ϵ_o is approximately

$$\bar{\epsilon} = (E/mc^2)^2 \epsilon_o \qquad (1)$$

Taking ϵ_o to be 2 ev for the average photon energy of starlight and $\bar{\epsilon} = 4$ Kev for the energy of the observed X-rays we find $E \approx 25$ Mev. The number intensity of recoil photons from a cloud with N electrons at a distance R and with a photon density n_s is

$$j_x = \frac{\sigma_\tau c N n_s}{4\pi R^2} , \qquad (2)$$

where σ_τ is the Thomson cross-section. These same electrons will suffer radiative collisions with the ambient protons with density n_p and give rise to an intensity of bremsstrahlung gamma rays which is about

$$j_\gamma = \frac{3\sigma_\tau}{137} \frac{cNn_p}{4\pi R^2} \ln 3 \qquad (3)$$

over a wide spectrum up to about 25 Mev. Combining (2) and (3) we can express the expected intensity of gamma rays in terms of the X-ray intensity by the relation

$$j_\gamma = \frac{n_p}{n_s} \frac{3 \ln 3}{137} j_x . \qquad (4)$$

By determining an upper limit on j_γ, one can place an upper limit on n_p in terms of the starlight density:

$$\bar{n}_p = \frac{137}{3 \ln 3} \frac{j_\gamma}{j_x} n_s . \qquad (5)$$

This limit can hardly be less than the density of electrons for otherwise the cloud would not be electrically neutral. Thus

$$\bar{n}_p > n_e \tag{6}$$

But the density of electrons is approximately

$$n_e = \frac{2N}{(R\,\theta)^3} \tag{7}$$

where θ is the observed angular diameter combining (2), (5), (6) and (7) one finds

$$R > \frac{24\pi\,\ln 3}{137}\;\frac{j_x^{\,2}}{c\sigma_\tau n_s^{\,2}\,\bar{j}_\gamma\,\theta^3} \quad . \tag{8}$$

Overbeck found $j_\gamma < .01$ in the energy range from 3.5 to 7 Mev and $j_\gamma < .01$ from 7 to 28 Mev (99% confidence). The recent investigation by Oda et al. of the SCO-X1 source with the modulation collimator demonstrated that $\theta < .002$ radians.[5] Rocket measurements give $j_x \sim 20\ \mathrm{cm}^{-2}\ \mathrm{sec}$.[6] We may reasonably assume $n_s < 1\ \mathrm{cm}^{-3}$. With these values in (8) one finds

$$R > 1 \times 10^{26}\ \mathrm{cm}$$

This puts the hypothetical electron cloud needed to produce the SCO-X1 X-rays by the inverse Compton process far outside the galaxy and probably beyond belief.

An exhaustive treatment of the data obtained in the energy range above 100 Mev from the Explorer XI gamma ray astronomy satellite has just been completed and will appear shortly in the Astrophysical Journal.[7] This experiment was prepared several years ago by W. Kraushaar and myself, and was launched in April 1961. It has since enlisted the efforts of several associates and students at MIT.

The final results from Explorer XI are essentially the same as those reported earlier in preliminary form.[8] However, they are now more adequately supported by a careful laboratory study of the angular and energy response of a duplicate instrument that was carried out with tagged gamma rays at the Cal Tech synchrotron, and by a thorough analysis of the dependence of the observed counting rate in orbit on those physical conditions which should affect differently the part which is due to true cosmic gamma rays, and any part which may be due to false events caused by charged primaries. The analysis was accomplished by means of a simple and highly flexible statistical method of Monte Carlo simulation that permits one to evaluate the effective exposure time of the instrument for any given range of the parameters that describe the situation in orbit.

We designed the instrument so that a gamma ray arriving from the forward direction gave a characteristic signature of pulses which we call a gamma ray event. Other forms of radiation could only very rarely forge this signature.

Ground tests on the duplicate instrument demonstrated that the response function representing the effective area for detecting gamma rays versus energy began at 50 Mev and rose to a plateau value of 7 cm^2 effective area at about 250 Mev. The angular response fell by a factor of 100 between 0^{o} and 60^{o}. The analysis of data obtained in orbit showed a maximum counting rate for gamma ray events in the horizon direction due to albedo gamma rays, and a plateau in this rate at angles greater than 63^{o} above the horizon, as shown in Figure 5. Whereas the albedo rate showed a variation with geomagnetic latitude as expected, the plateau rate was constant within the poor statistics.

The total number of gamma ray events recorded when the axis of the detector was more than 63^{o} above the horizon was 31. Taking into account the total exposure time, and assuming that the detected radiation is gamma rays with a differential energy spectrum of the form $W^{-\gamma}$ with $\gamma = 1.7$, we find an average integral intensity for $W > 100$ Mev of

$$I = 2 \times 10^{-4}\ cm^{-2}\ sec^{-1}\ sterad^{-1}.$$

In the absence of more definite proof as to the nature of the radiation that causes the gamma ray events this value must be considered only an upper limit to the true integral intensity. It is, in fact, ten times higher than the rate expected from the interaction of cosmic rays with interstellar matter in the galaxy, assuming the distribution of atomic hydrogen determined from radio observations and also assuming a density of cosmic rays throughout the galaxy equal to the local density. The ratio of the average intensity within 45^{o} of the galactic plane to the average intensity within 45^{o} of the galactic poles is

$$\frac{I\ (b > 45^\circ)}{I\ (b < 45^\circ)} = 1.6 \pm 0.6$$

There is no evidence in the data of gamma radiation from various possible point sources such as Cygnus A, the galactic center, etc. Typical upper limits on the possible fluxes are about 10^{-3} cm^{-2} sec^{-1}.

In the range of energies above 10^{14} ev the only feasible approach to gamma ray astronomy is the study of the extensive air showers which energetic primary photons generate when they enter the atmosphere. The major difficulty with this approach is that ordinary charged primary cosmic rays, which are tremendously more frequent, also generate extensive air showers. However, ordinary cosmic rays are protons or nuclei, and they generate mixed nucleonic and electromagnetic showers. These mixed showers contain, on the average, about 1% of penetrating mu-mesons near their cores. In contrast, showers initiated by primary gamma ray photons are nearly pure electromagnetic showers and contain only about .01% of penetrating particles that arise from photomeson production. The problem therefore comes down to searching for "low-mu" showers, i.e., extensive air showers with unusually few penetrating particles. This can be done with an air shower detector array operated in anticoincidence with a penetrating particle detector of very large area.

A group from MIT, the University of Tokyo, the University of Michigan and the St. Andres University in La Paz, Bolivia has set up an experiment called the Bolivian Air Shower Joint Experiment (BASJE) whose main purpose has been to search for gamma ray air showers.[9] The air shower detector consists presently of twenty 1 m^2 scintillation detectors in an array 600 m in diameter set out around the Laboratory of Cosmic Physics is at an altitude of 17,000 feet on Mt. Chacaltaya near La Paz. The penetrating particle detector is a 60 m^2 scintillation detector covered with 200 tons of concrete and galena (PbS). The shielding ensures the complete absorption of all electromagnetic radiation that strikes the 60 m^2 area. The detectors underneath are sensitive enough to measure a single particle traversing any place in the 60 m^2 area. The air shower array gives data from which the arrival direction can be determined within $\Delta\,\theta \sim 3^{\circ}$, the core location within $\Delta\,R \sim 2$ m, and the size within $\Delta\,N/N \sim .1$.

We have studied the distribution in penetrating particle content of a large number of showers with sizes in the range from 5×10^5 to 4×10^6 corresponding roughly to primary energies from 10^{15} ev to 10^{16} ev. We selected showers whose cores were far enough from the 60 m^2 detector so that local fluctuations in structure near the core did not affect the measurements. We also required that the expected total number of particles striking the 60 m^2 detector on top of the shielding exceed 1400. The observed distribution in penetrating particle content (Figure 7) shows that the average value was about 10^{-2}, which, for a shower of minimum acceptable size, corresponds to 14 observed penetrating particles in the 60 m detector. The distribution at low values gives evidence for the existence of a distinct class of "low-mu" showers whose penetrating particle content is less than 10^{-3} as expected for pure electromagnetic showers. The relative proportion of these "low-mu" showers among all showers is between 1.5×10^{-3} and 3×10^{-4}, depending on where the dividing line is placed. Firkowski et al.[10] have also searched for low-mu showers in an experiment at sea level, and they have reported positive results at 10^{16} ev.

On the basis of the evidence presently available one cannot prove that the nearly pure electromagnetic showers observed in this experiment are caused by primary gamma rays. One cannot exclude the possibility that they arise in rare nuclear interactions of primary protons in which nearly all of the primary energy is transferred to a neutral pi-meson which decays into two gamma rays. The clearest evidence in favor of a gamma ray origin for some of the events would be an observation of some form of anisotropy -perhaps a concentrated source or a tendency to cluster near the Milky Way where we can expect a higher rate of production. In Figure 8 we have plotted the arrival directions as dots on a celestial map. We have also compared their distribution in galactic latitude with the one expected on the basis of the exposure time. In neither case is there significant evidence of anisotropy.

If one assumes that the primaries of the observed low-mu showers are photons, then the relative proportion of photons among all cosmic ray primaries in the energy range from 10^{15} ev to 10^{16} ev is between 5×10^{-4} and 1×10^{-4}, when account is taken of the different rates of development for pure electromagnetic and mixed showers.

An interesting prospect for the future of the BASJE is the conclusion which may be drawn from data now being recorded on the relative proportion of "low-mu" showers above primary energies of 10^{16} ev. Photons of this energy can arise from neutral pi-mesons produced in photonuclear interactions between protons over 10^{17} ev and starlight. If the abundance of protons at this energy is universal, then the metagalactic production of $> 10^{16}$ ev photons by this process may give an appreciable flux at the earth. Conversely, if the BASJE observations place a low upper limit on the relative proportion of "low-mu" showers above 10^{16} ev, then it may be possible to place significant upper limits on the metagalactic density of cosmic rays over 10^{17} ev. In any such analysis the attenuation of the gamma rays by collision with metagalactic infra-red and microwave photons will have to be taken into account.

Figure Captions

Figure 1. The observed counting rates in the five pulse height channels plotted against the azimuth of the detector axis measured with respect to the azimuth of the Crab Nebula.

Figure 2. Expected and observed relative counting rates in the five channels for various assumed incident spectra. The expected rates are normalized to the observed value in Channel III.

Figure 3. Summary of observational data on the electromagnetic spectrum of the Crab Nebula.

Figure 4. Schematic diagram of the apparatus used in a search for gamma rays from the X-ray source in Scorpio.

Figure 5. Counting rate for gamma ray events from the Explorer XI satellite plotted as a function of the angle of the detector axis from the horizon.

Figure 6. Comparison between the observed intensities of gamma ray events at different galactic latitudes (circles) and the intensity expected from interactions between cosmic rays and the interstellar hydrogen in the galaxy (dark line).

Figure 7. Relative frequencies of extensive air showers with various proportions of penetrating particles as observed at 17,000 feet altitude.

Figure 8. Celestial arrival directions of showers which were in the lowest 10^{-3} fraction in penetrating particle content. The concentration of events between declinations -55 and +30° is the result of atmospheric absorption which limits the effective field of view to zenith angles of less than about 45°.

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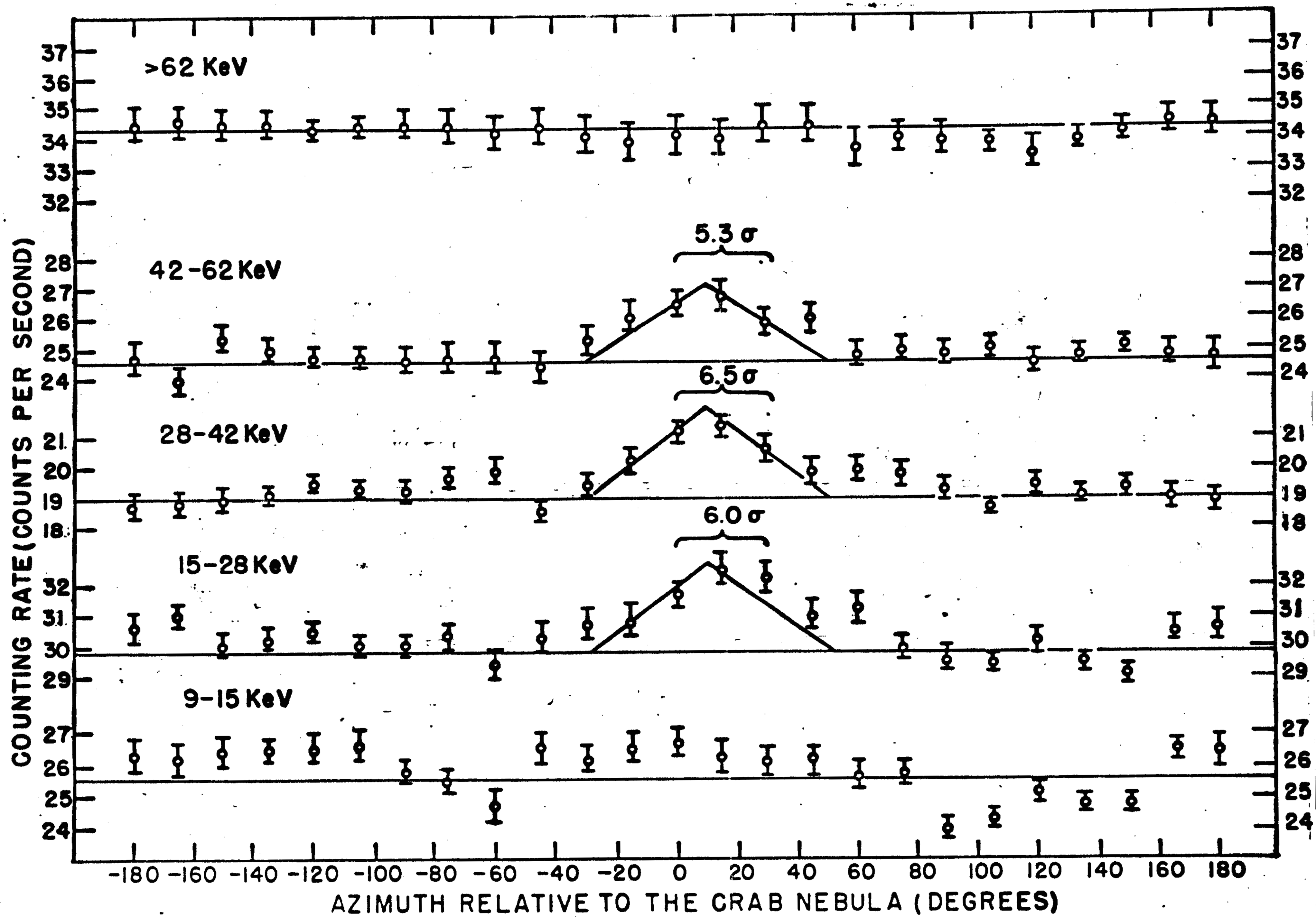
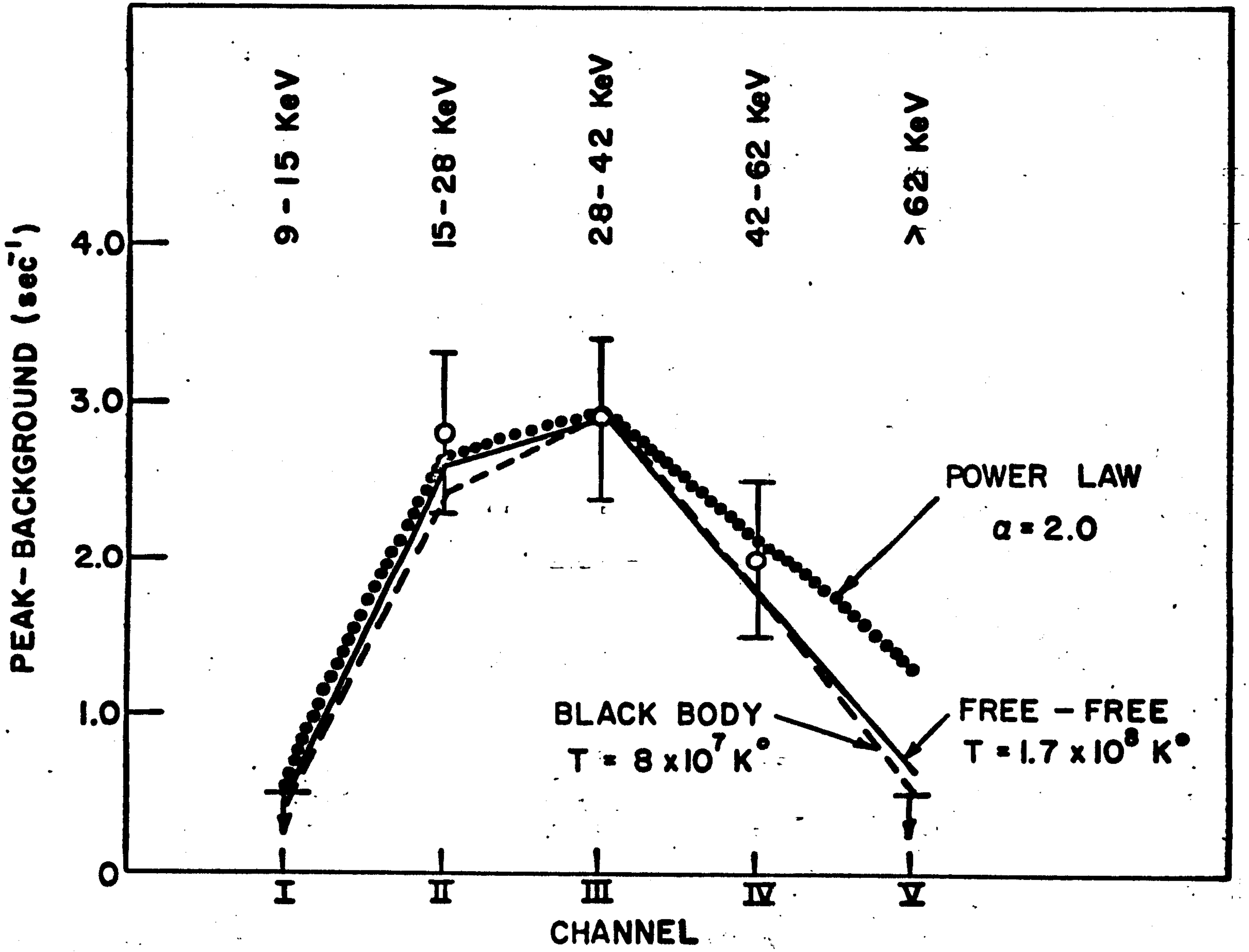
(1)

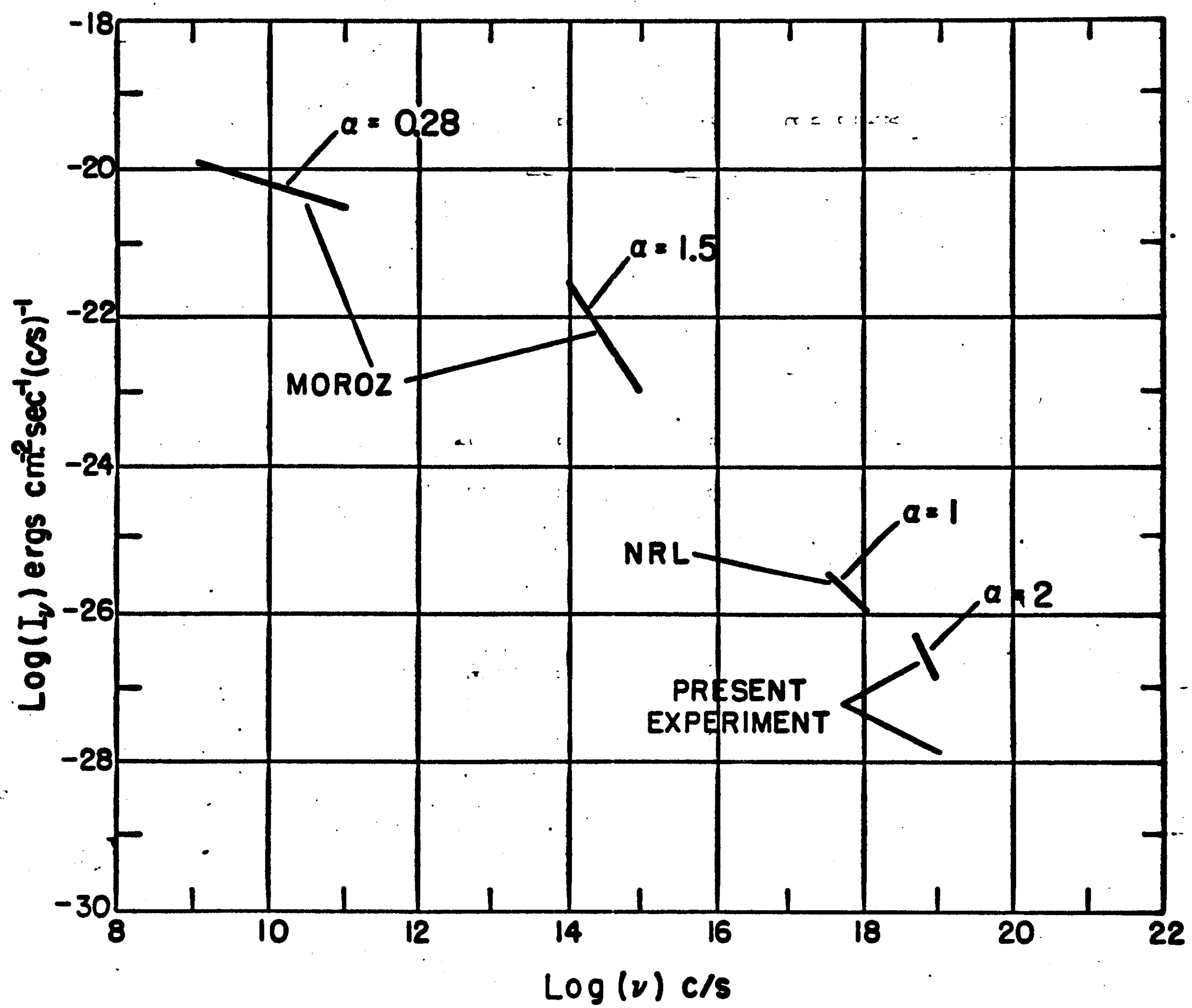

>62 KeV
42-62 KeV
28-42 KeV
15-28 KeV
9-15 KeV
5.3 σ
6.5 σ
6.0 σ
COUNTING RATE (COUNTS PER SECOND)
AZIMUTH RELATIVE TO THE CRAB NEBULA (DEGREES)

(2)

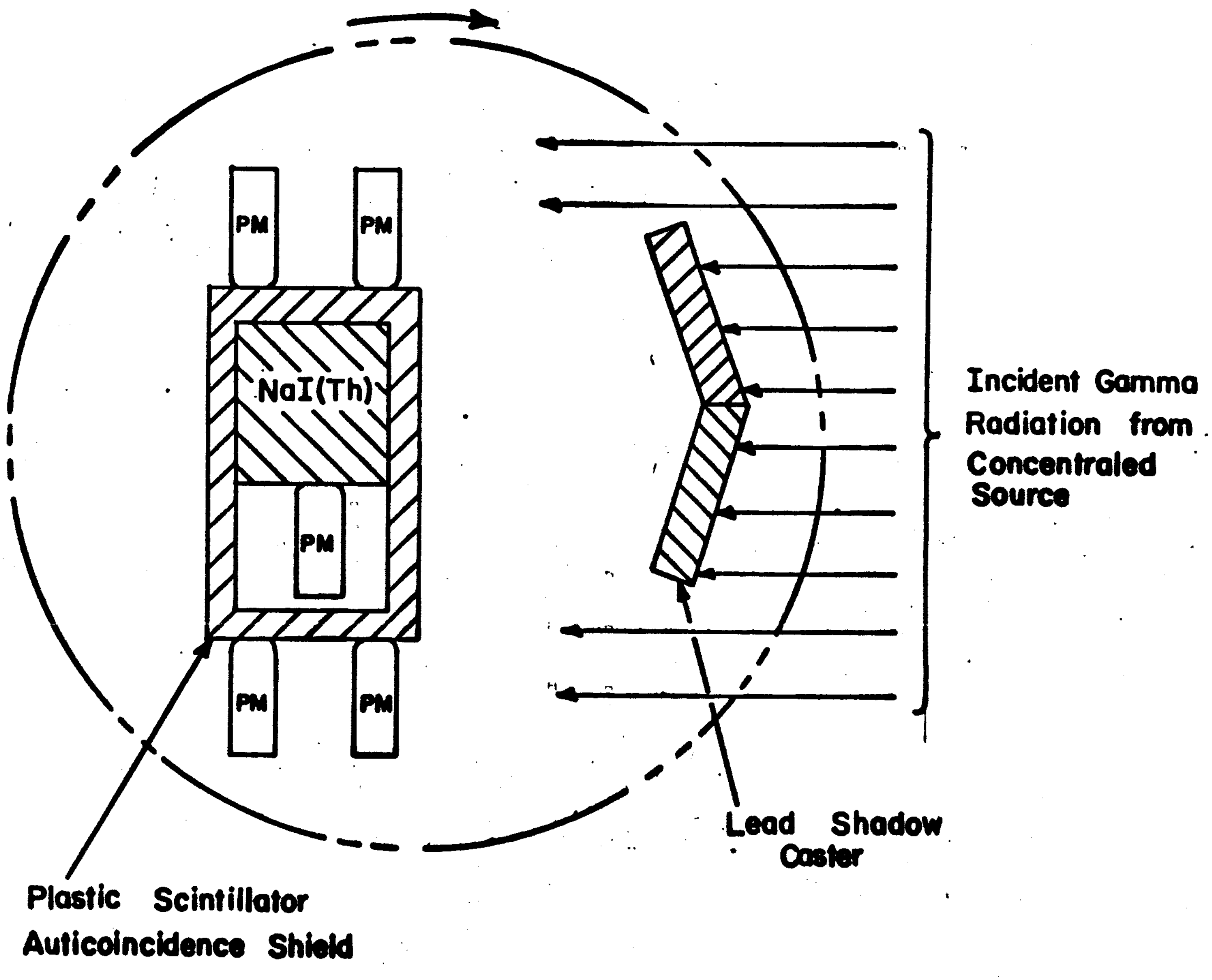


COMPARISON BETWEEN OBSERVED COUNTING RATES AND THOSE EXPECTED FOR INCIDENT SPECTRA OF THREE KINDS WITH PARAMETER ADJUSTED FOR BEST FIT

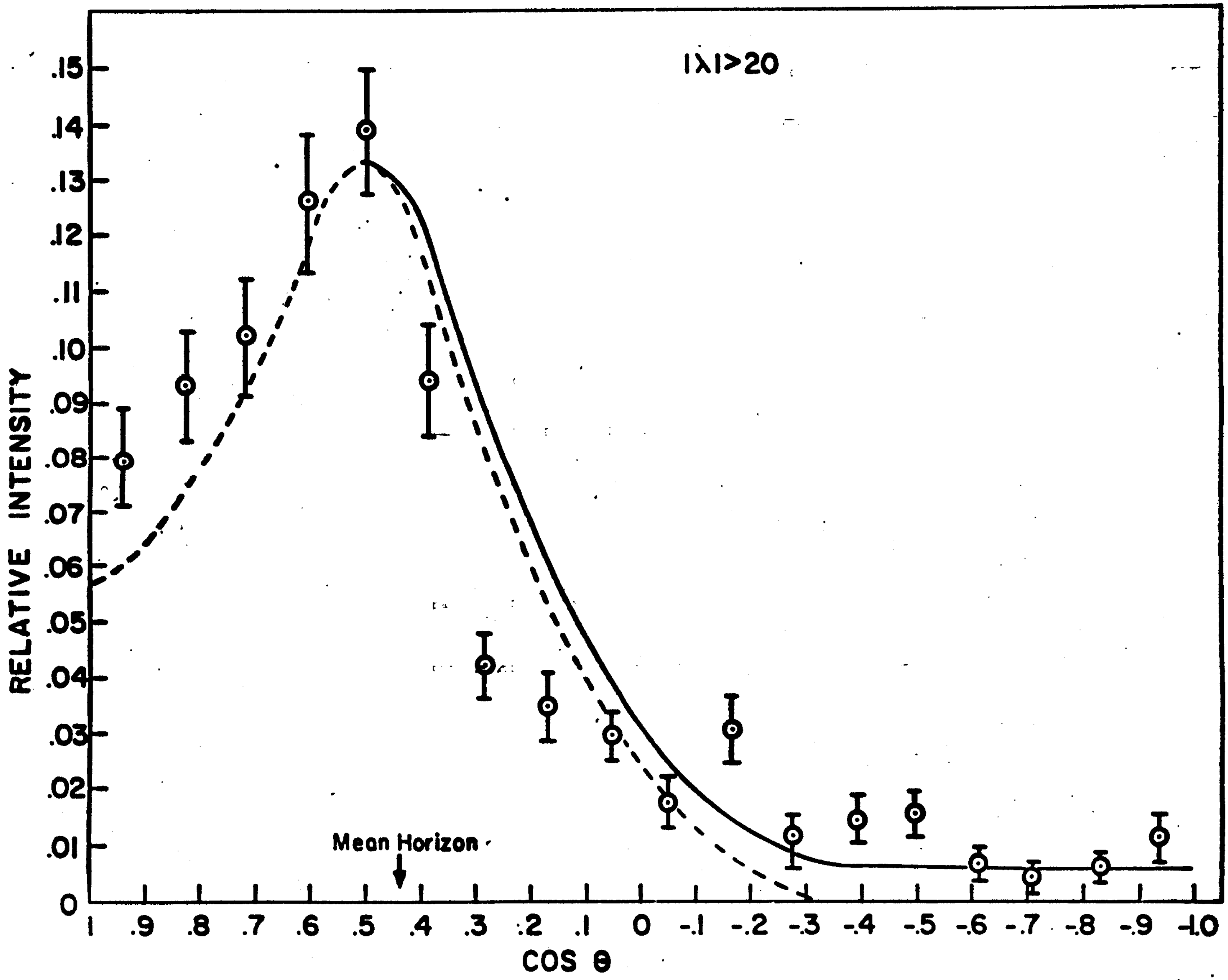
(3)



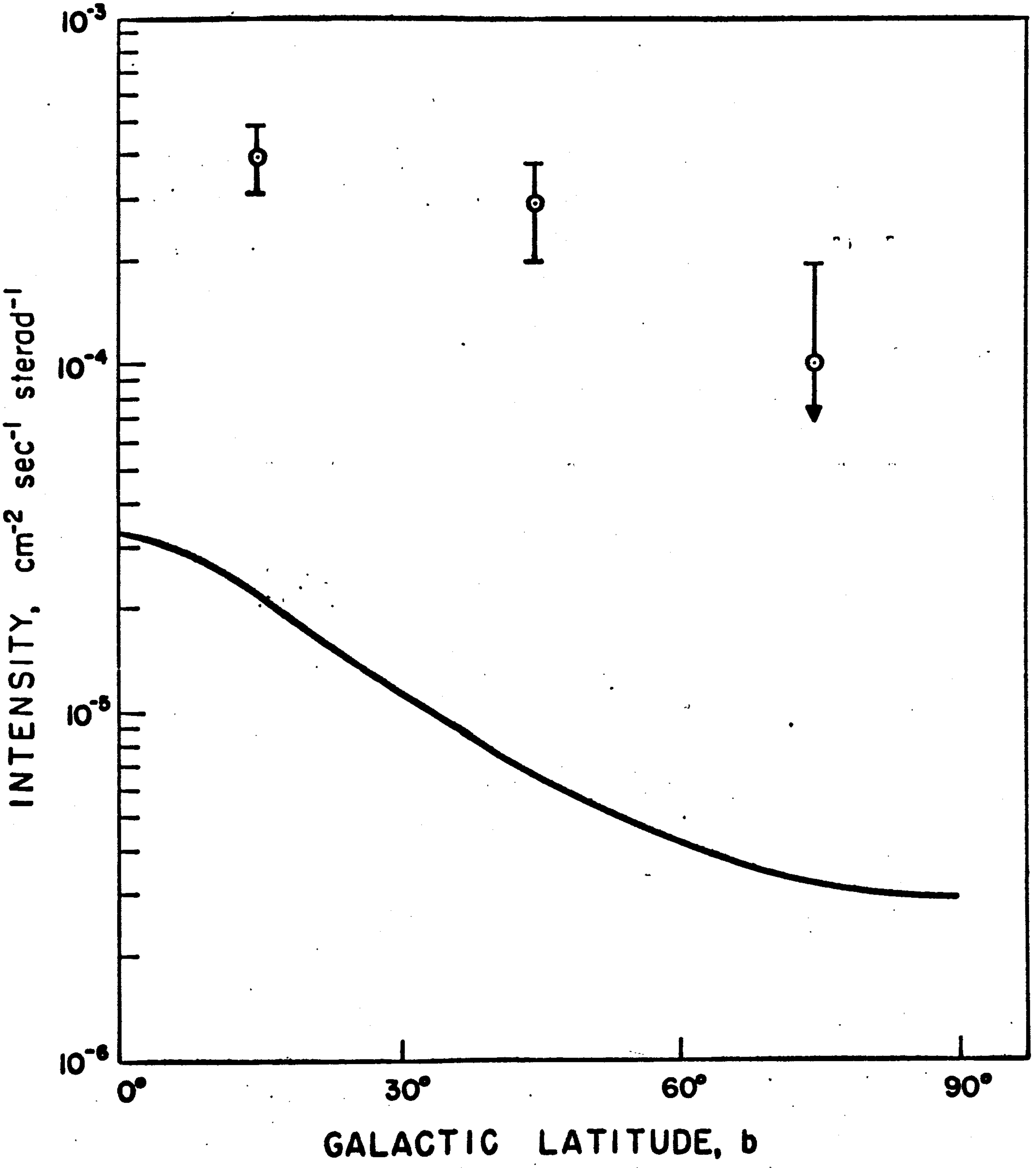
-18
-20
-22
-24
-26
-28
-30
8
10
12
14
16
18
20
22
Log(Iν) ergs cm-2 sec-1 (c/s)-1
Log (ν) c/s
α = 0.28
α = 1.5
MOROZ
NRL
α = 1
α = 2
PRESENT EXPERIMENT


PM
PM
NaI(Th)
PM
PM
PM
Incident Gamma Radiation from Concentraled Source
Lead Shadow Caster
Plastic Scintillator Auticoincidence Shield

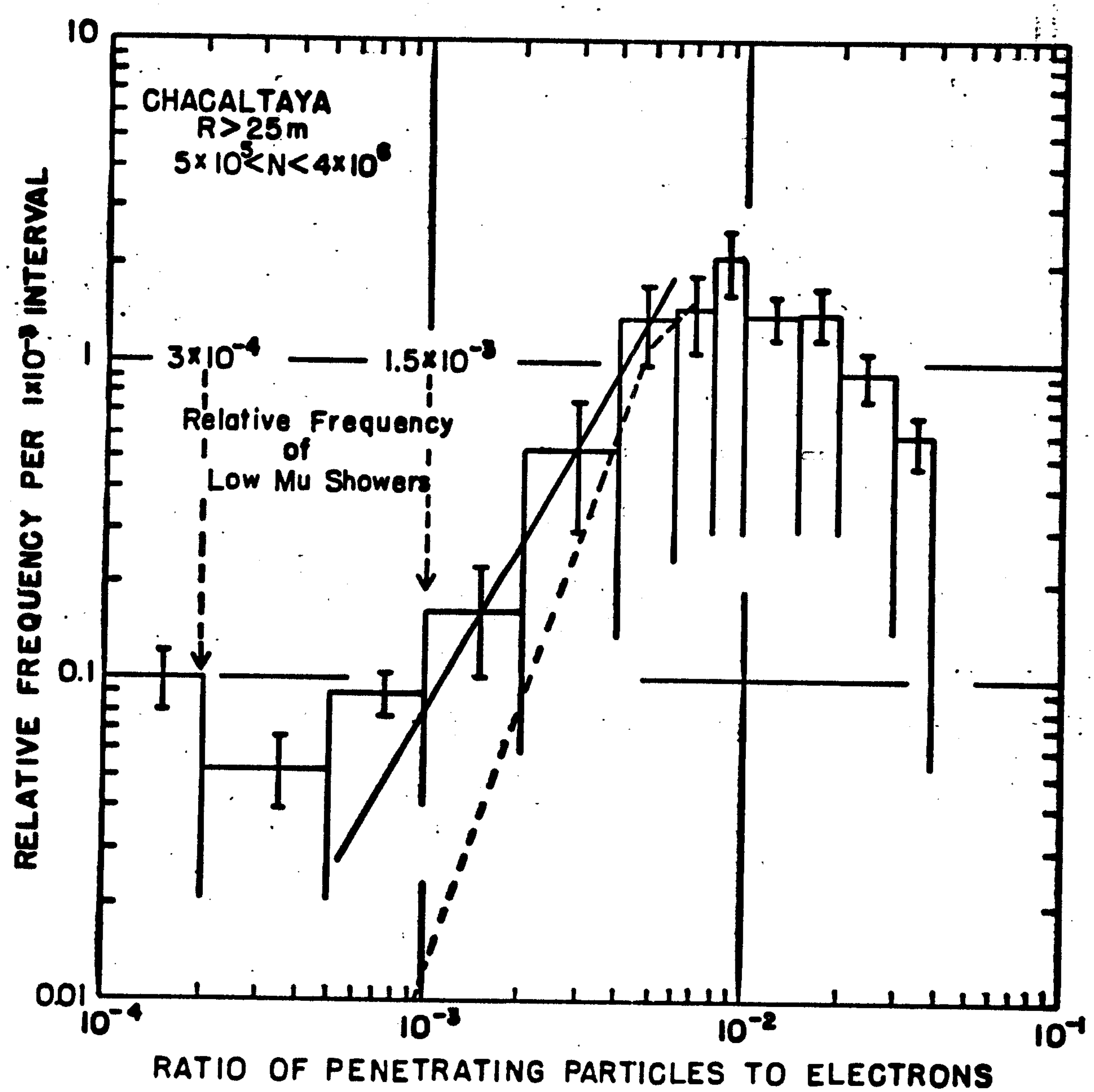
5



|λ|>20
RELATIVE INTENSITY
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
1 .9 .8 .7 .6 .5 .4 .3 .2 .1 0 -.1 -.2 -.3 -.4 -.5 -.6 -.7 -.8 -.9 -1.0
Mean Horizon
COS θ

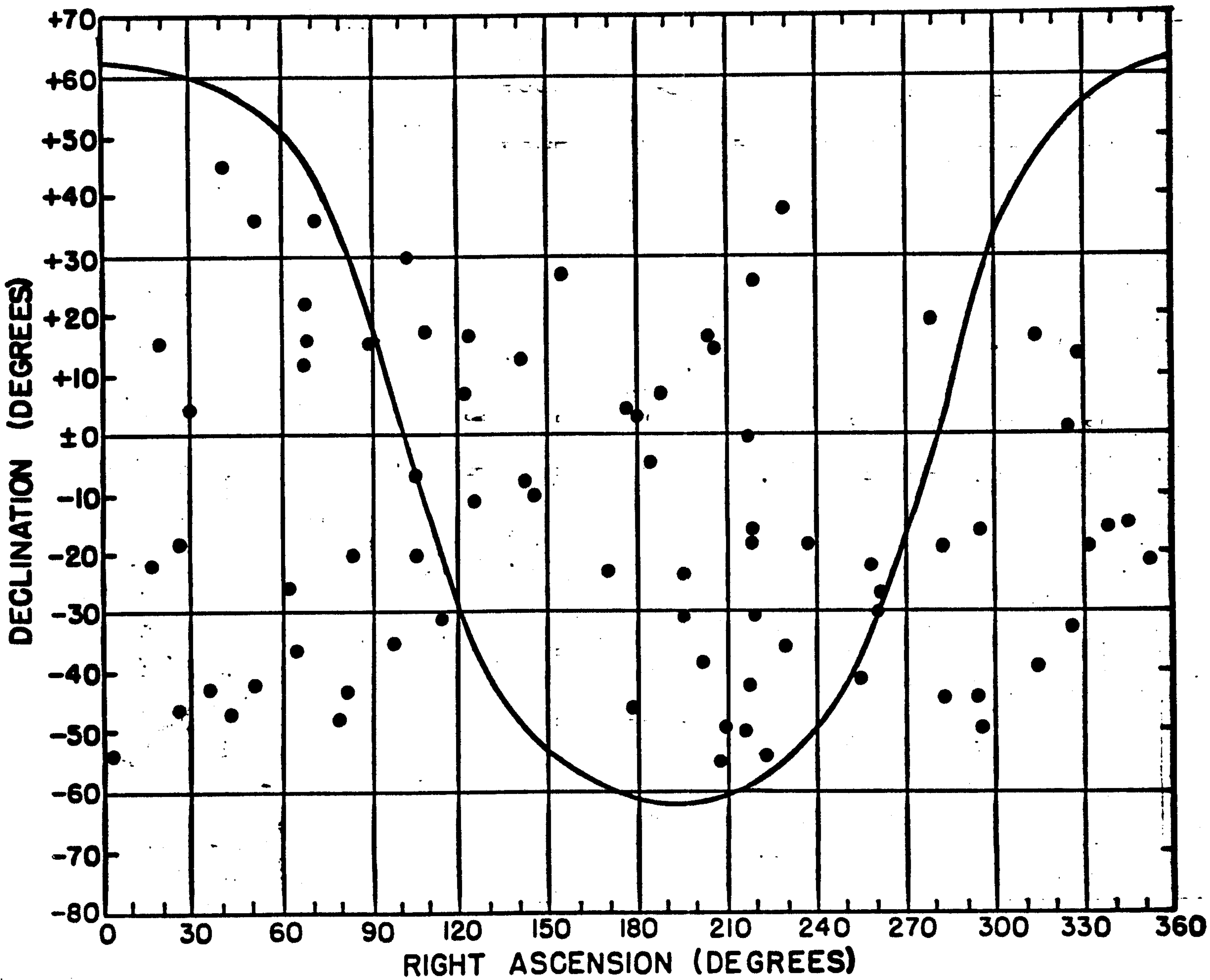


10^{-3}
10^{-4}
10^{-5}
10^{-6}
INTENSITY, cm^{-2} sec^{-1} $sterad^{-1}$
0°
30°
60°
90°
GALACTIC LATITUDE, b



CHACALTAYA
R>25m
5×10^5<N<4×10^6
3×10^-4
1.5×10^-3
Relative Frequency of Low Mu Showers
RELATIVE FREQUENCY PER 1×10^-3 INTERVAL
RATIO OF PENETRATING PARTICLES TO ELECTRONS
10
1
0.1
0.01
10^-4
10^-3
10^-2
10^-1

(8)



DECLINATION (DEGREES)
+70
+60
+50
+40
+30
+20
+10
±0
-10
-20
-30
-40
-50
-60
-70
-80
0
30
60
90
120
150
180
210
240
270
300
330
360
RIGHT ASCENSION (DEGREES)

Lwp # 8